Printed Antenna Designs Using Defected Ground Structures: A Review of Fundamentals and State-of-the-Art Developments

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***Abstract*— Deliberately created defects in the form of etched-out patterns on the ground plane of microstrip circuits and transmission lines have been familiar to microwave engineers for a long time, although their applications to the antennas are relatively new. The term Defected Ground Structure (DGS), specifically implies a single or very limited number of defects. The antenna designers initially employed DGS underneath printed feed lines to suppress higher harmonics. During 2005-2006, DGS was directly integrated with antennas to improve the radiation characteristics and to suppress mutual coupling between adjacent elements. Since then, the DGS techniques have been explored extensively and have led to many possible applications. Over 1200 technical papers, three book chapters, and several granted patents on 'antennas with DGS', produced in a short span of last eight years, are a measure of the potential of this technique. The objective of this work is aimed to address the topic in a comprehensive way, to provide a chronology of the research and innovations, to offer an insight of the technology, and to review the state-of-the-art advances in the area of DGS.**

***Index Terms*— Defected Ground Structure, DGS, defected ground plane, antenna with DGS, DGS integrated array, printed monopole with DGS.**

I. INTRODUCTION

DURING the last decade there have been significant advances in Wireless Technology, which demands the availability of efficient devices that can be operated at high data-rates and at low signal powers. Microwave researchers have been working towards the development of advanced RF front ends to meet the requirements. Various novel approaches have been explored to improve the performance of printed circuits and antennas.

In this article, we describe a recently developed technique called the Defected Ground Structure (DGS) approach for designing low profile antennas such as microstrip and dielectric resonator antennas. The DGS can be regarded as a simplified form of Electromagnetic Band Gap (EBG) structure [1], from which it evolved. It exhibits a band-stop property and its area of application involves microstrip transmission lines and circuits. Kim and Park [2] first proposed and used the term 'DGS' in describing a single unit of dumbbell-shaped defect. A chronology of its development is thoroughly discussed in [3]. Subsequently, three more recent books [4]-[6] have addressed the topic of antenna design using the DGS.

DGS has become a promising alternative to EBG for different applications due to its compact nature and easy implementation. Initially, dumbbell-shaped DGSs were used to realize a filter [7], and shapes were experimented with subsequently to realize different microwave circuits such as filters [8]-[12], amplifiers [13], rat race couplers [14], branch line couplers and Wilkinson power dividers [15], [16], and details on these designs may be found in [3].

The DGS was first directly integrated with a microstrip radiator in 2005 [17] in order to improve its radiation characteristics. A series of subsequent investigations explored the possibility of using DGS technology to address different printed antenna problems [3]. The popularity of this technique has grown immensely amongst antenna engineers, who have extended the DGS-based technique to monopole UWB antennas [18]-[26], Planar Inverted 'F' Antenna (PIFA) antennas for mobile handsets [27]-[28], dielectric resonators [29], phased arrays [30], RFID tag antennas [31], etc. Different research groups are currently active in developing newer and even more applications of DGS to various antenna design problems.

The technical contents of this work are organized for presentation in seven sections. Section II deals with the general ideas and working principle of DGS, and presents commonly used geometries and their modeling in terms of circuit equivalents. Subsequent sections (III-VI) touch on possible applications of DGS that have been developed till date.

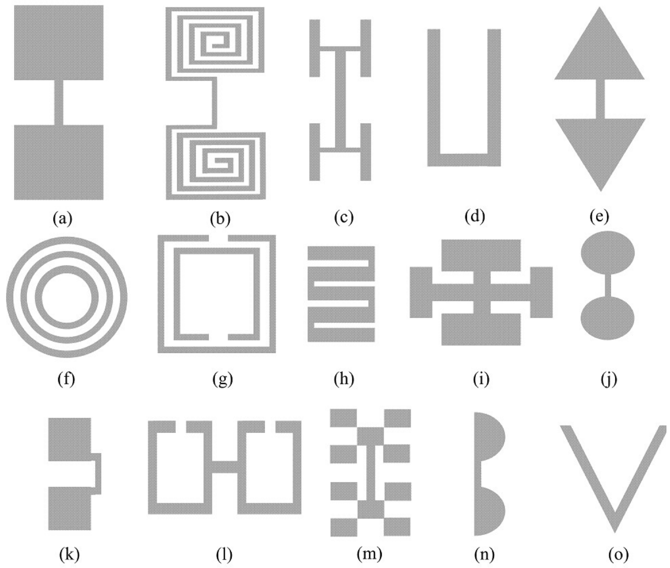

Fig. 1. Different DGS geometries: (a) Dumbbell-shaped (b) Spiral-shaped (c) H-shaped (d) U-shaped (e) Arrow head dumbbell (f) Concentric ring shaped (g) Split-ring resonators (h) Meander line (i) Cross-shaped (j) Circular head dumbbell (k) Square heads connected with U slots (l) Open loop Dumbbell (m) Fractal (n) Half-Circle (o) V-shaped.

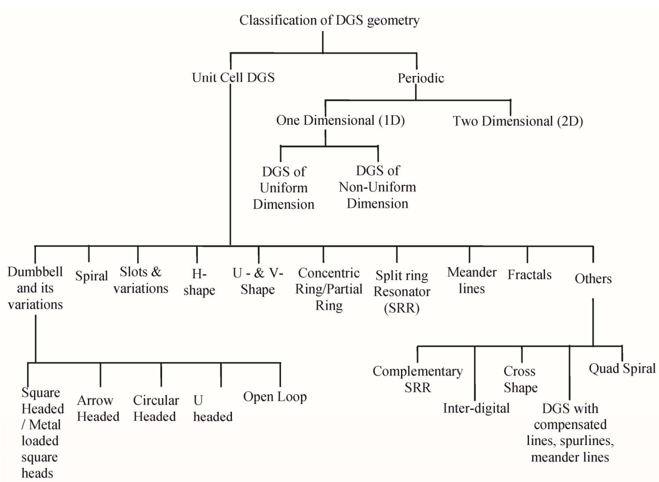

Fig. 2. Some basic classification of DGS geometries.

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II. BASIC IDEAS AND GEOMETRIES

The DGSs refer to certain compact geometrical shapes and they are realized in the form of defects on the ground plane of printed circuits. The DGS may either comprise a single defect (unit cell), or it may contain a number of periodic and aperiodic configurations. A DGS is characterized by its stop-band behavior within which it impedes the propagation of electromagnetic (EM) waves through the substrate containing the DGS over a range of frequencies. Different configurations of DGS have been explored with various applications in mind and some of these are discussed below along with the modeling techniques for them.

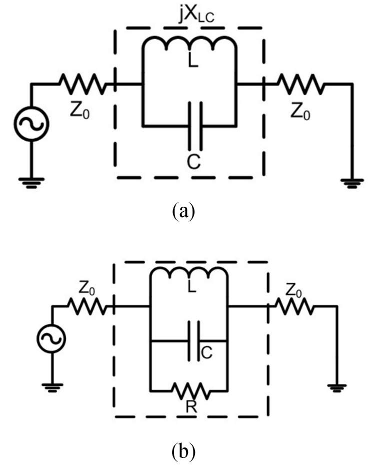

Fig. 3. Equivalent circuit representation of DGS (a) LC parallel combination, (b) LCR parallel combination.

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A. Geometries and Working Principle

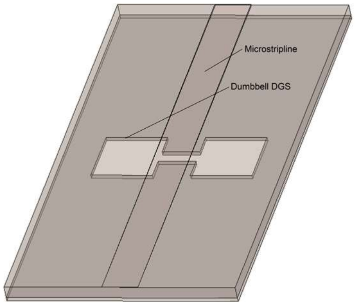
A DGS may come in a variety of geometries and sizes, depending upon their mode of application, as well as the frequency of operation. These shapes include: rectangular dumbbell [2], circular dumbbell [32], spiral [33], ‘U’ [34], ‘V’ [34], ‘H’ [35], cross [36], concentric rings [37], etc., and are illustrated in Fig. 1. Some complex shapes have also been studied which include meander lines [38], split ring resonators [39], [40], and fractals [41]. Fig. 2 shows a flow-chart type of their classifications.

Conventionally, in planar microstrip circuits, a DGS is located beneath a microstrip line and it perturbs the electromagnetic fields around the defect. Trapped electric fields give rise to the capacitive effect (*C*), while the surface currents around a defect cause an inductive effect (*L*). This, in turn, results in resonant characteristics of a DGS, and it is important for us to determine the equivalent circuits and associated parameters, as discussed below. Acquainted

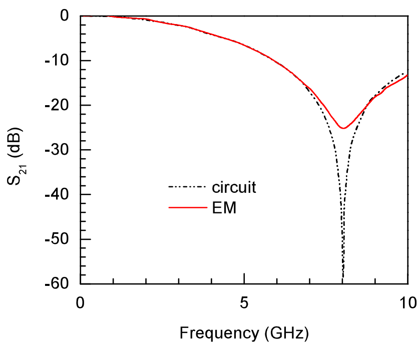
B. Modeling Techniques

A quantitative analysis is needed to understand the performance of a DGS or to extend the design by cascading multiple units of the same DGS. An equivalent circuit is helpful in this regard, and the modeling methods can be classified into following three categories: (a) transmission line modeling [42]; (b) LC and RLC circuit modeling [7] and [43]; and (c) quasi-static modeling [44]. The second one appears to be more general and it is relatively straightforward to model a DGS in terms of equivalent parallel LC or RLC circuits, as shown in Fig. 3. The equivalent parameters are the functions of the defect dimensions. The simple example of a dumbbell-shaped DGS has been discussed in [7]. For the ‘dumbbell’ geometry in Fig. 4, the rectangular head on either side of the line introduces a series inductance L, and the narrow slot beneath the line produces a gap capacitance C in parallel with L. the extraction of these parameters is discussed below and has also been presented in [7].

Typically, an EM simulator is utilized to determine the S-



(a)



(b)

Fig. 4. (a) Dumbbell shaped DGS integrated with microstrip transmission line, (b) Simulation results for the DGS unit. Parameters: square head sides a=b= 5 mm, connecting slot width g= 0.5mm, h=31 mils and ε_r = 2.2 [7].

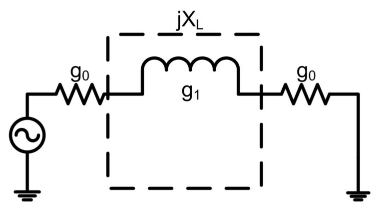


Fig. 5. Butterworth one-pole prototype low-pass filter.

parameters of a circuit. The attenuation pole is located at 8 GHz with 3dB cut off at 3.5 GHz as shown in Fig. 4(b). It displays a response similar to that of a single-pole Butterworth LPF, shown in Fig. 5. The reactance of the equivalent circuit in Fig. 3(a) can be expressed as

$$X_{LC} = \frac{1}{\omega_o C}\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right) \quad (1)$$

where ω_0 is the angular resonant frequency, and the reactance of the LPF in Fig. 5 is given by

$$X_L = \omega_I Z_0 g_I \quad (2)$$

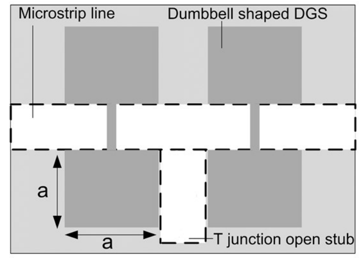
where ω_I is the normalized angular frequency, Z_0 is input and output port impedances, and g_I is the prototype element [45]. Equating (1) and (2) at the cutoff, we have

$$X_{LC}\,|_{\omega=\omega_c} = X_L\,|_{\omega_1=1} \quad (3)$$

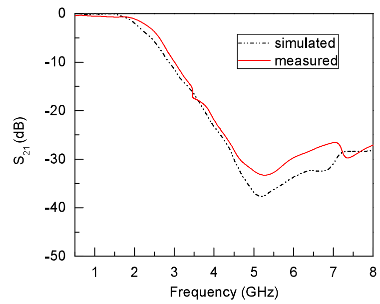
$$C = \frac{\omega_c}{Z_0 g_1}\left(\frac{1}{\omega_0^2 - \omega_c^2}\right) \quad (4)$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \quad (5)$$

where f_0 is the resonant frequency for the DGS as well as the attenuation poles of the Butterworth prototype.



(a)



(b)

Fig. 6. Low pass filter with cascaded dumbbell shaped DGS integrated with microstrip transmission line along with T-junction stub (a) schematic diagram, (b) simulated S parameters [7].

The LC modeling presented herein does not account for any losses attributable to either radiation, conduction, or dielectric. More realistic models include a loss resistance R, as shown in Fig 3(b). It is important to note that, the values of L, C, and R do not have any definite relationship with the dimensions of the DGS. Consequently, it is neither possible to derive accurate dimensions of a DGS from the knowledge of its desired frequency response, nor it can provide any clues to how we might obtain the parameters of the equivalent circuit. This issue has been addressed in [44], and for further information, we refer the reader to [3], [44].

III. DGS AS FILTER USED IN ANTENNA FEEDS

In the early phases of its development, a majority of DGS shapes were explored to design printed circuit filters, and these applications inspired the antenna engineers to realize planar feeds with stop-band characteristics by employing DGS-integrated microstrip feeds. The primary application was to control the higher harmonics when a microstrip patch was integrated with an oscillator or an amplifier that shared the same substrate. It is well known that active circuits are prone to be affected by undesirable harmonics; however, the DGS-integrated feeds can suppress these unwanted frequency bands. Different configurations have been explored since 1999 to achieve this goal and they are discussed below.

A. DGS Filter

A dumbbell-shaped DGS was used in [7] to design a low pass filter. Two DGS units were integrated with a microstrip line as depicted in Fig 6. The S-parameters shown in Fig. 6 are self-explanatory. The basic concepts of DGS were further explored subsequently to develop several new DGS configurations [34]-

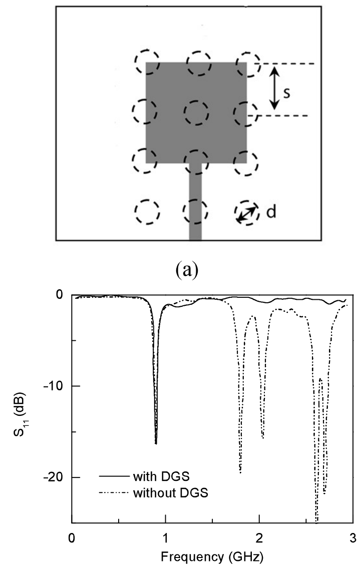


Fig.7. Microstrip line fed microstrip patch integrated with array of circular DGS (a) schematic diagram, (b) simulated S-parameters with and without DGS [46].

[36], [38]. In addition, an account of the circuit applications of DGS was provided in [3].

B. DGS-integrated Microstrip Feed

To suppress higher harmonics, in 1999 Horii and Tsutsumi [46] used defects in the ground plane underneath the feed as well as below a microstrip patch. They used a 3×4 array of circular defects in the ground plane as shown in Fig. 7(a). Measured return loss characteristics with and without the DGS are shown in Fig. 7(b). The antenna operates at 900 MHz and the defect diameter is 1/18 of the operating wavelength (λ = 33.33 cm). This enables the 900 MHz signal to propagate, while suppressing the frequencies ranging from 1760 MHz to 2720 MHz, and achieving levels of S_{21}<-20dB. Specifically, two harmonics near 1800 MHz and 2700 MHz are suppressed. A similar square patch was investigated in [47] with a change in the DGS configuration below the feed line. Circular defects were replaced by dumbbell-shaped DGSs, as shown schematically in Fig. 8(a), to widen the stop-band and the effectiveness of the DGS over a wider frequency band.

Chang and Lee [43] proposed a simpler design as shown in Fig. 8(b). They removed all the defects underneath the patch and obtained the desired stop-bands to control the harmonics. Further simplification in terms of number of DGS units was explored by Sung and Kim [48]. They used a single dumbbell-DGS underneath the feed, as shown in Fig. 8(c). Its radiation characteristics indicate a considerable level of suppression (> 15 dB) of the first harmonic. Considerable back radiation was evident in their study, and this issue has been discussed in [3].

An even more compact design was realized in [49], where the DGS was placed at the neck of the inset feed shown in Fig. 8(d). This configuration has the advantages that it does not use any additional space and that it suppresses up to the first harmonic.

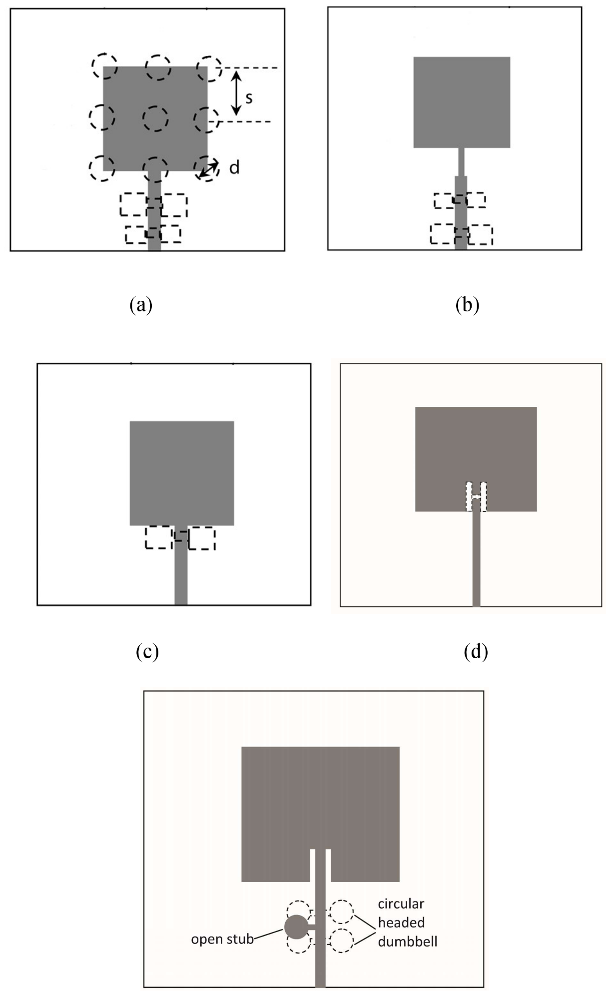


Fig. 8. Microstrip line fed square patch antenna integrated with (a) circular and dumbbell shaped DGS [47], (b) double dumbbell DGS[43], (c) single dumbbell [48], (d) H shaped DGS [49], (e) circular headed dumbbell and stub [50].

A different approach for improving the stop-band with the aim of suppressing up to the third harmonic was examined by Mandal *et al*. [50]. Their design includes a stub-line along with a pair of dumbbell-shaped DGS, whose schematic view is shown in Fig. 8(e). Rejection of frequencies up to the third harmonic of the fundamental was experimentally demonstrated in [50].

The problem of reducing the physical area of a DGS has been addressed in a recent investigation carried out by the present authors [51], who used partial ring DGSs shown in Fig. 9, for this purpose. This configuration occupies about 50% reduced space as compared to other reported designs, but does not compromise the performance within the band of operation. Excellent rejection of the modes covering up to the 3rd harmonic has been reported in [51] and suppression of radiation at these harmonics has been experimentally demonstrated in [51].

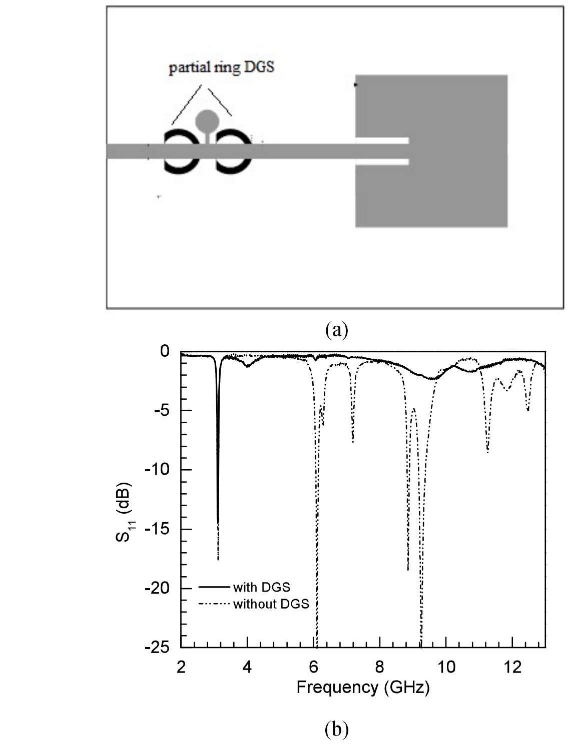


Fig. 9. Square patch antenna fed with partial ring DGS integrated microstrip line, (a) schematic diagram, (b) measured S_{11} versus frequency of the patch with and without DGS [51].

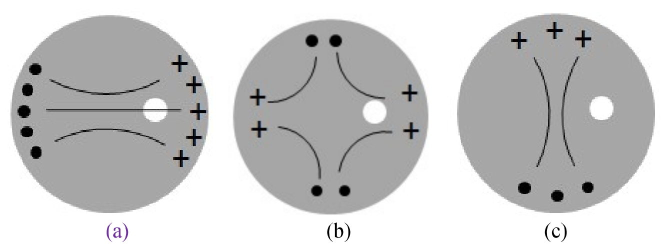


Fig. 10. Field and surface current distributions in a circular microstrip patch for different modes; + and ● indicated the electric fields between patch and ground: surface currents are shown using solid lines; white dot indicates the location of the feed probe. (a) TM_{11} mode: X-polarized (dominant mode), (b) TM_{21} mode , (c) Orthogonal component of dominant mode (OCDM): Y-polarized TM_{11} (sense of x-axis and y-axis are shown in Fig. 11).

IV. DGS FOR ANTENNA DESIGN

A new application of DGS was first conceived and proposed by Guha *et al.* in 2005 [17], with a focus on the suppression of cross-polarized (XP) radiations in a circular microstrip patch by using DGSs. Their approach was based on the known theory of XP radiations according to which a higher order mode is responsible for generating the XP fields. First two modes in a circular patch are sketched in Fig. 10 in which TM_{21} is identified as the XP-generating mode, which results in significant radiations in the H-plane. Theoretically, this mode cannot explain the radiation of XP in the E-plane, but this issue was resolved in [17]. A weak orthogonal resonance (y-polarized TM_{11}), indicated in Fig. 10(c), was identified as the cause of this unavoidable XP radiation in the E-plane.

In the investigation of [17], a pair of small 'circular-dot' shaped DGS was strategically placed underneath a circular patch in the H-plane, as shown in Fig. 11. Their centers exactly coincide with the patch boundary, and the diameter $2r$ is close to $0.07\lambda_0$. The DGSs indeed perturb the electric boundary condition on the ground plane, and prevent the excitation of orthogonally generated TM_{11} fields, sketched in Fig. 10 (c). This conjecture was verified, and confirmed experimentally, with a set of prototypes operating around 3.6 GHz. The measured radiation patterns, shown in Fig. 12, indicate an improvement of about 5 dB in the XP-isolation without affecting the co-polarized radiations.

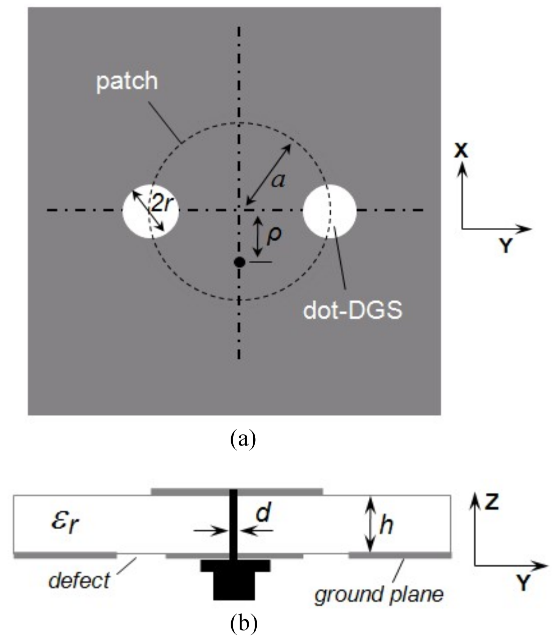


Fig. 11. Configuration of a circular microstrip antenna integrated with dot-DGS; (a) view from ground plane side, (b) cross-sectional view [17].

Effectiveness of these 'dot-DGS' was investigated in more details in [52], [53]. It was observed that the small size dot-DGSs were effective in suppressing only the E-plane XP. But the primary concern of significant XP level in the H-plane, which is caused by the TM_{21} mode, could not be addressed during the first attempt by using the dot-DGS. However, this aspect was subsequently investigated by the same group, who employed some innovative techniques that are discussed below.

V. INNOVATIONS IN ANTENNA APPLICATIONS: 2006-2013

A. *Reduction of Cross-polarized Radiation*

Circular and Elliptical Patches

From Fig. 10(b), one can surmise that the fringing fields associated with the TM_{21} mode are not localized over a small region; rather they are widely distributed surrounding the patch boundary instead. Therefore, rather than using a localized dot-DGS, it is more effective to employ an elongated DGS along the patch contour to interact with the XP-generating fields.

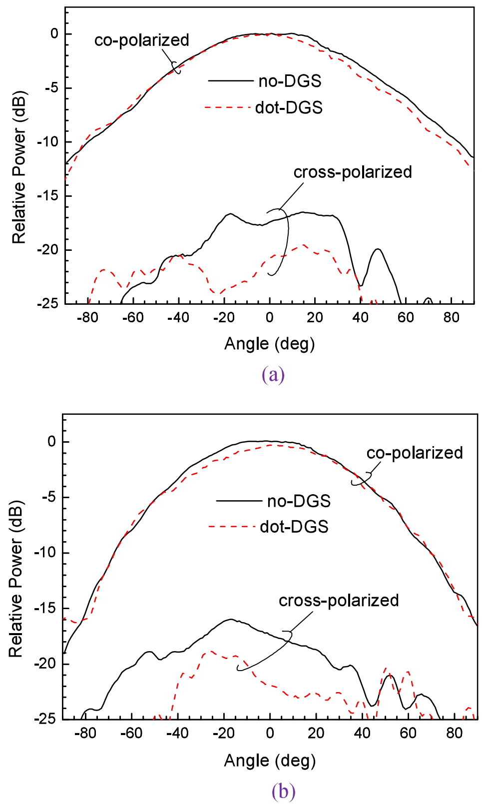


Fig. 12. Measured radiation patterns of a probe-fed circular patch with and without dot-DGS. Parameters: a = 15 mm, ρ = 5 mm, $2r$ = 6 mm, d_p= 0.76 mm, h = 1.575 mm, ε_r = 2.32, ground plane: $0.7\lambda_0 \times 0.7\lambda_0$; (a) E-plane, (b) H-plane: freq. 3.6 GHz [17].

This idea was extended, and led to the development of a circular-ring-shaped DGS, shown in Fig. 13(a) [53]. This improves the H-plane XP radiation by about 4-5 dB, though further improvement is limited. Such a DGS cannot be placed at a close proximity of the patch boundary since that may weaken the primary radiating mode.

To overcome this limitation, the shape of the DGS was modified to the geometry of an 'arc' [54], as indicated in Fig. 13 (b). Such an arc-shaped DGS sets the dominant mode (fields along the E-plane) free from the possibility of being affected by the DGS. Therefore, an arc-type DGS can now be placed very close to the patch to destroy the TM_{21} mode. Improvised DGS with levels of 9-10 dB suppression of the XP fields in the H-plane but without affecting the primary radiations has been reported in [54] and [55]. H-plane radiation patterns of a C-band antenna with and without arc-DGS, are shown in Fig. 14. This approach which works over the entire operating band of the antenna, was verified in [53], [54], and a set of representative results are presented in Fig. 15. Arc-DGS integrated circular patch is found to have more than 30 dB of isolation in the C-band [54], and 25 dB in the X-band [53] over a wide range of azimuth angles.

Arc-DGS suppression has also been examined for elliptical patches with varying eccentricity [56], and the design information, developed through elaborate studies [53]-[56] is as follows: (i) width of arc-DGS is strictly determined by the operating wavelength and substrate parameters, but not by the antenna geometry; (ii) and the value of α (≈ 65.5°, Fig. 13 (b))

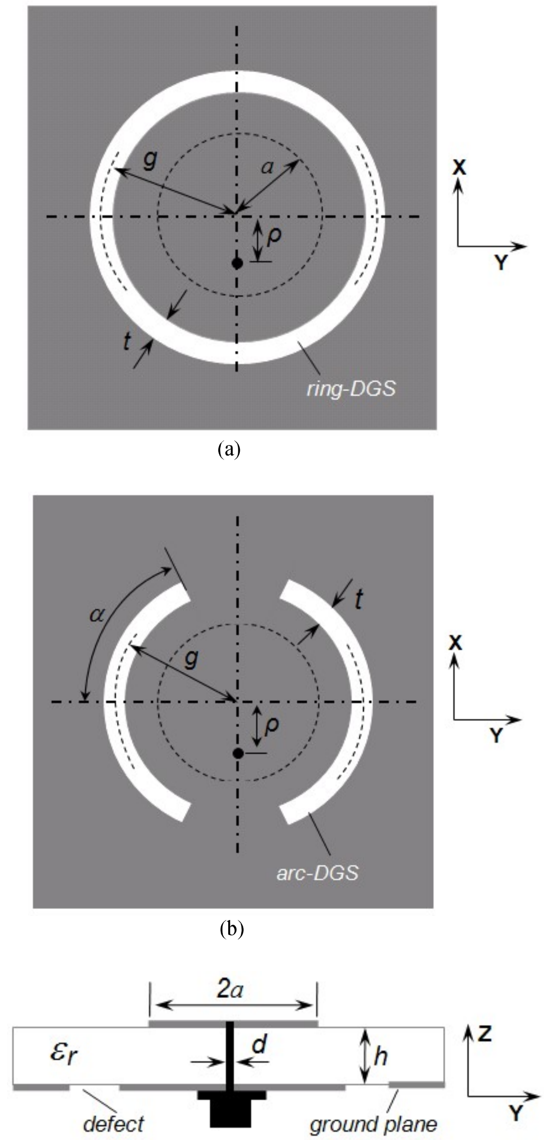


Fig. 13. Configuration of a circular microstrip antenna integrated with DGS; (a) ring-DGS [53] and (b) arc-DGS; as viewed from ground plane side, (c) cross-sectional view [54]

is constant for a circular patch whose diameter can be arbitrary.

Square and Rectangular Patches:

In the early phase of its development, the dot-DGS was directly used for a rectangular patch as well [57]. That group followed the work in [17] and reported reduction in boresight XP, based on the simulated data.

The design methodology of arc-DGS was extended to rectangular patches with varying aspect ratios (W/L) [58], [59]. The W/L values that have been tested include: W/L=1 (square patch); W/L < 1 (narrow patch); and W/L > 1(wide patch). The mode responsible for producing the XP radiation in rectangular patches is TM_{02}. To interact with its fields, a DGS needs to follow the patch boundary and, hence, it takes the shape of square brackets ('[' and ']'), as shown in Fig. 16. Therefore, it is referred to as 'folded-DGS', and its working principle is the same as that of the 'arc-DGS'. It significantly

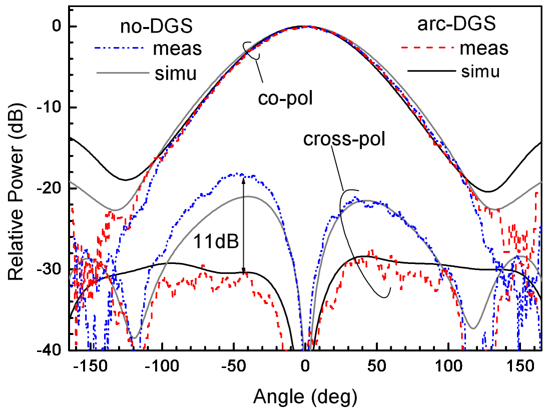


Fig. 14. Measured and simulated H-plane radiation patterns of a probe-fed circular patch with and without arc-DGS. Parameters: a = 9 mm, h =1.575 mm, d =1.5 mm, ρ= 2.8 mm, ε_r = 2.33, g = 10 mm, t =2 mm, α = 66˚, ground plane: $1\lambda_0\times 1\lambda_0$; freq. 5.9 GHz [54].

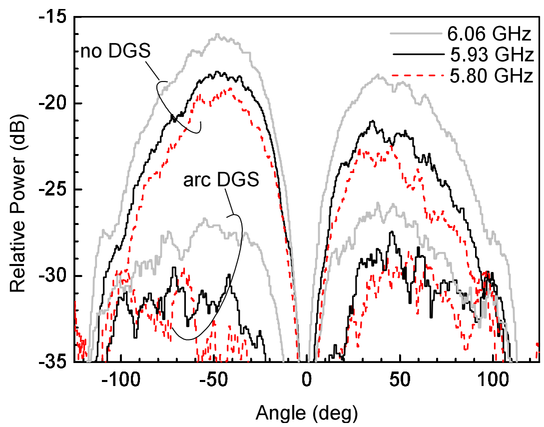


Fig. 15. Measured cross-polarized radiation patterns over the frequency band (S_{11} ≤ -10 dB) of the circular patch with and without arc-DGS. Parameters as in Fig. 14.

suppresses the radiation of XP in the H-plane, while leaving the primary radiation relatively unaffected. One example of a rectangular patch with W/L = 1.6 is shown in Fig. 17, where H-plane XP fields are suppressed by about 23 dB. Several interesting results and design information are available in [59], and we ask the readers to refer to the same.

Triangular Patch:

Controlling the XP fields originating in triangular patches was investigated in [60]-[61]. Different DGS shapes were explored and an example [61] is shown in Fig. 18. This antenna operates in a circular polarization (CP) mode, where the DGSs takes care of the polarization purity as well as widening of the axial ratio bandwidth. Improvement in impedance bandwidth along with gain has also been claimed in the above studies.

Microstrip Slot Antennas:

DGS has been improvised to realize microstrip slot radiator. A 'V-shaped' DGS has been employed [62] on a 1.575 mm thick substrate, with ε_r = 2.33, to operate the antenna in the 7-8 GHz band. Measured results indicate a suppression of 10-12 dB in the XP radiations, in both the principal planes.

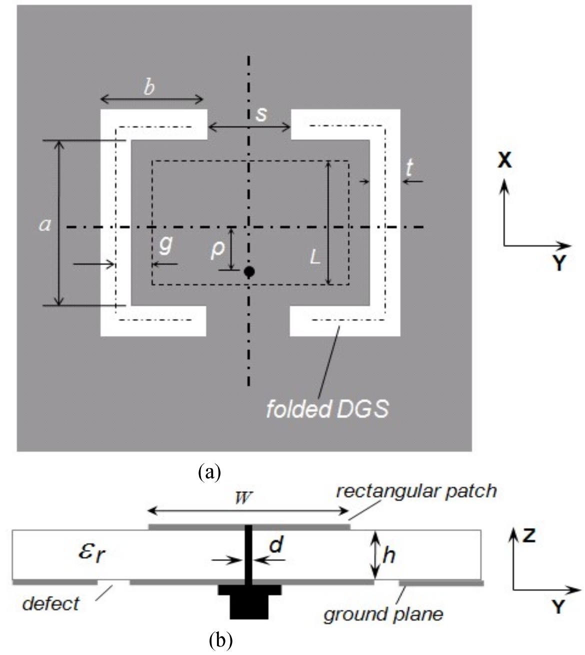


Fig. 16. Configuration of a rectangular microstrip antenna integrated with folded-DGS; (a) view from ground plane side, (b) cross-sectional view [59].

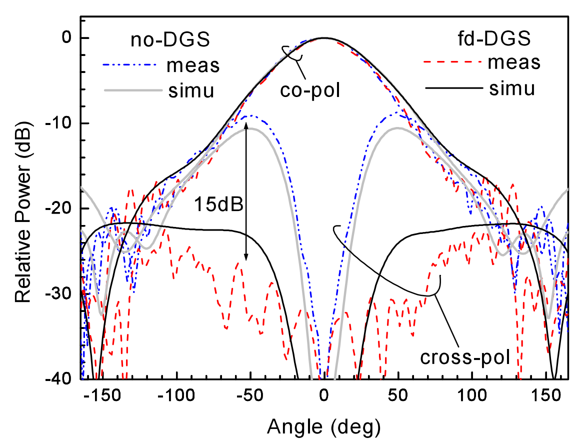


Fig. 17. Measured and simulated H-plane radiation patterns of a probe-fed rectangular patch with and without 'folded-DGS'. Parameters: L = 8.6 mm, W = 13.76 mm, ρ = 3.1 mm, t = 1.5 mm, g = 0 mm, s = 6 mm ground plane 60 mm × 60 mm; h = 1.575 mm, ε_r = 2.33; freq. 10.1 GHz.

B. Suppression of Mutual Coupling and Array Applications

So far we have discussed about DGS-integrated patches and slots where they have been used to control their XP radiation. Soon after the pioneering paper published in 2005 [17], the same group proposed another major application of DGS in 2006 [37]. The authors first showed how the DGS could be employed to reduce the mutual coupling between two adjacent microstrip patches. In [37], the use of concentric ring DGS was explored for an array of circular patches. Another contemporary work [63] focused on a similar approach by using a different geometry.

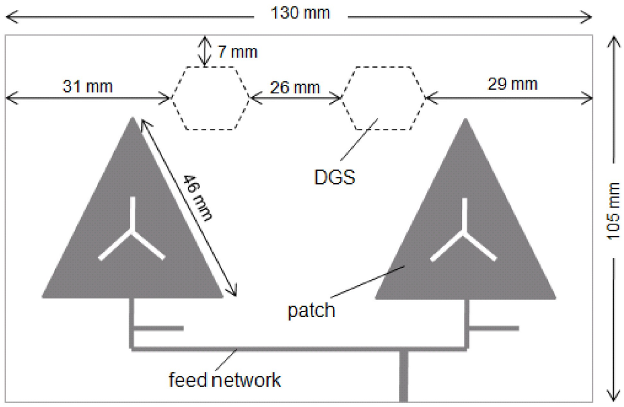


Fig. 18. Diagram of a 2×1 array of triangular patch integrated with hexagonal DGS (top view). Parameters: area of each DGS 129.5 mm², substrate thickness = 1.57 mm, ε_r = 2.2, freq. 2.61 GHz [61].

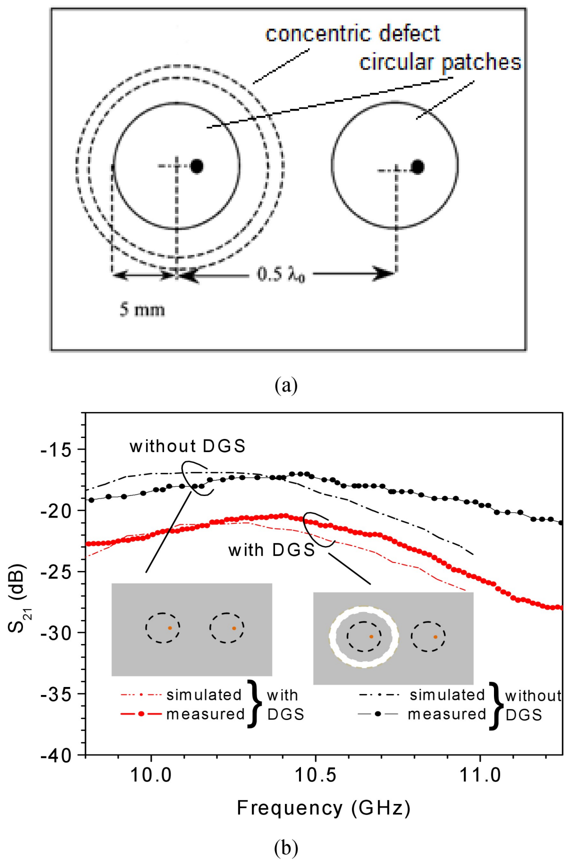


Fig. 19. (a) Single ring-shaped DGS between two-element E-plane coupled circular microstrip patch [37] (b) Measured and simulated S_{21} versus frequency [64].

Mutual coupling appears to be one of the major issues in planar arrays, since it introduces unwanted features in the radiation patterns such as scan blindness and high side lobe levels because of introduction of the surface waves that are undesirable. The stop-band property of DGS becomes useful for controlling the surface waves, when inserted between adjacent radiating elements. Based on this idea Guha *et al.* have explored [37], [64] the possibility of using a configuration shown in Fig. 19(a). Figure 19(b) shows the S_{21}

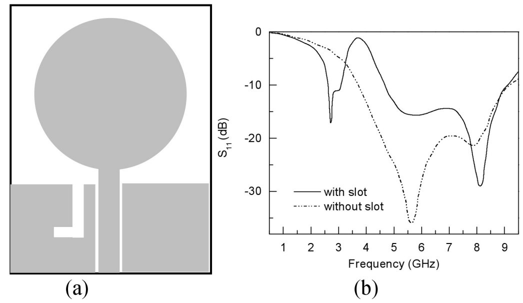


Fig. 20. (a) Printed circular disc monopole antenna with L-shaped DGS, (b) Simulated S_{11} versus frequency of the antenna with and without DGS [18].

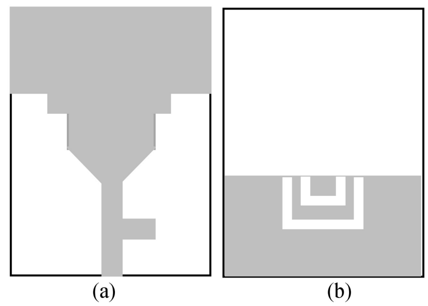


Fig. 21. Printed microstrip monopole antenna with double U shaped DGS (a) Top view, (b) Bottom view [19].

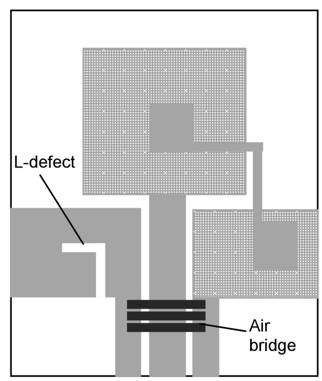


Fig. 22. Printed monopole antenna with L shaped DGS and metamaterial loading [21].

characteristics, and indicates a 4-5 dB reduction in the mutual coupling. The same concept was extended to Dielectric Resonator Antennas (DRAs) array showing a similar reduction in mutual coupling in the E-plane [65]. Salehi *et al.* [63] have experimented with dumbbell-shaped DGS for rectangular patches etched on a high permittivity substrate and have demonstrated a significant reduction in the mutual coupling. Such configurations were later used for designing sensors for the detection of land mines [66]. Multiple units of dumbbell-DGS have been explored in [67] for multiband antennas and have realized up to 5 dB of suppression.

An important application of DGS was reported for phased arrays in [68]. The authors obtained 'Scan blindness' near 33° for a six-element rectangular patch array with a conventional ground plane and they were able to eliminate the scan

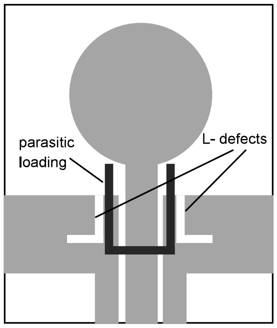


Fig. 23. CPW fed circular monopole antenna with double L shaped DGS and parasitic U shaped element [22].

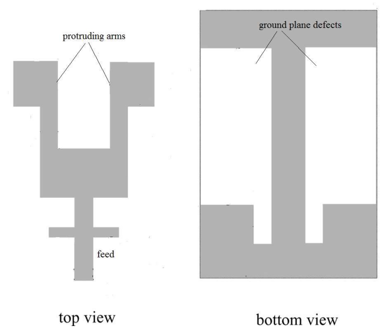


Fig. 24. Schematic configuration of tri-band printed monopole antenna with DGS [25].

blindness by using dumbbell-shaped DGS [68]. This approach has been further examined and confirmed by others [69] (see for instance), both for a finite (7×3) and an infinite phased array [70]. These examples serve to demonstrate a high potential of the DGS when employed in advanced array designs.

It should be noted, however, that designing and characterizing such DGSs is not very straightforward. Conventionally, a DGS is characterized in terms of its stop-band property, when placed underneath a microstrip line. However, such a DGS behaves in a completely a different way when it is used to lower the coupling effects and is placed between two antenna elements. This issue has been recently investigated by the present authors [71], and they have proposed a realistic method which can provide a reliable solution based on a study of an isolated DGS. The method has also been experimentally verified for two E-plane-coupled DRAs [71], and for microstrip patches [72].

C. *DGS for Printed Monopole and UWB Antennas*

In 2008, two research groups [18], [19] explored the DGS, almost concurrently to design printed monopoles. However, their motivation for using the DGS was totally different from those in earlier applications. The authors of [18] employed defects in a CPW fed circular disc monopole to achieve a compact ground plane, as well as multiband operation. The L-shaped defect in the ground plane, shown in Fig. 20(a), resonates around 3.1 GHz in the absence of a slot, and in the presence of a wide ground plane ($\sim\lambda_g/2$). But, in monopole arrays, commonly used in MIMO/WLAN applications, it is desired that the size of the antenna be sufficiently small. However, a reduced size ground plane degrades the low-frequency response of the monopole, which is improved by

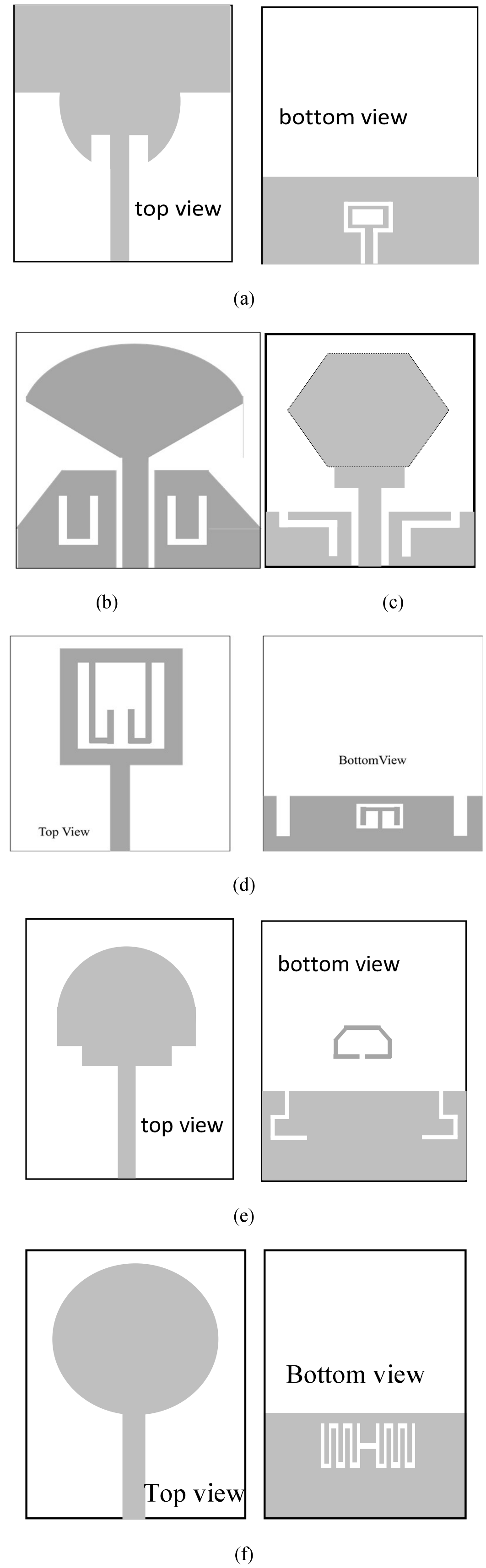


Fig. 25. Schematic diagram of different monopole antennas integrated with DGSs.

introducing an L-shaped DGS, shown in Fig. 20(a). It is relevant to note that the newly introduced DGS hardly affects the high frequency response of the antenna. Representative S_{11} characteristics with and without the DGS are presented in Fig. 20(b), to illustrate the role of the DGS.

In [19], another attempt was made to enhance the matching bandwidth of a trapezoidal monopole. The DGS was used as a resonator at a number of specific frequencies and to radiate at these frequencies. The antenna, shown in Fig. 21, operates over 790 to 2060 MHz covering nearly 112% impedance bandwidth. Soon after the publication of this work, the same group reported a tunable DGS-integrated monopole [73]. Tuning of the antenna at frequencies ranging from 2.7 GHz to 2.1 GHz was verified experimentally in this work.

The L-shaped DGS was further explored to achieve a tri-band operation, employing an interesting configuration comprising of metamaterial loading [21]. The geometry of the antenna is shown in Fig. 22. Such an L-shaped DGS is found to be attractive for similar designs. The use of a dual L-shaped defect was explored in a CPW-fed planar monopole in [22]. The above designs also added parasitic loading structures for matching as well as for the purpose of modifying the radiation characteristics. The configuration in [22], depicted in Fig. 23, is a representative example of the same. The DGSs and parasitic loadings are responsible for achieving resonances in specified application bands, such as WiMAX (3.5 GHz) or WLAN (5.2GHz/5.8GHz). A relatively simpler though interesting work was reported in [25], where the DGS renders the ground plane a radiating structure and realizes a triple-frequency operation as shown in Fig. 24 [25].

Another important application of DGS is to introduce either a single or multiple stop-bands in UWB operation of a printed monopole [20], [23], [24], [74]-[76]. Such stop-bands are needed to avoid interference from Bluetooth/WLAN (2.4/5.2/5.8 GHz), WCDMA (2.1GHz), and WiMAX (3.5/5.5 GHz) bands, which fall within the specified UWB band, with the DGSs serving as band-notch filters. The number of stop-bands varies depending on the shape and patterns of the DGS. Six examples are schematically shown in Fig. 25 based on the studies carried out in [20], [23], [24], [74]-[76]. The configurations shown in Figs. 25 (a), (b), (c) result in a single stop-band. The strategy for designing these antennas is based upon the fact that the DGSs, shown in Fig. 25 (d)-(f), offer multiple notches, while their dimensions determine the stop-band frequencies.

D. DGSs for RFID Tags

Recently, DGSs have also been used for the 4th generation chipless RFID tags [31]. The idea is to use multiple defects in the ground plane underneath a printed monopole in a way such that each DGS provides a spectral signature in the backscatter signal. Multi frequency signals are to be used as 'interrogating signals' and the detection is based on the variations in the magnitude and phase of the backscattered signals. A representative diagram of the configuration is shown in Fig. 26. This novel approach using simple DGS geometries should have high potential in realizing low-cost tags, printed on a plastic substrate by using a transparent but conductive ink.

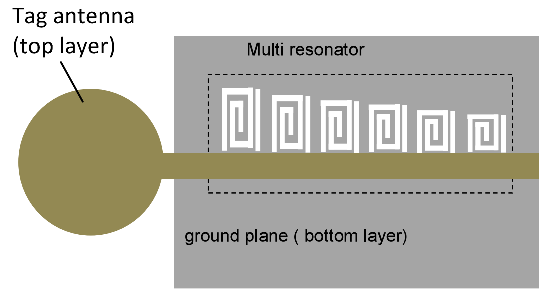
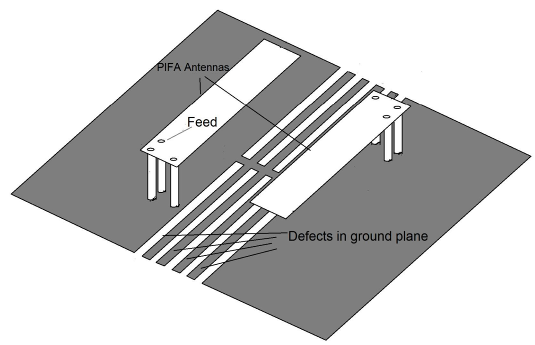
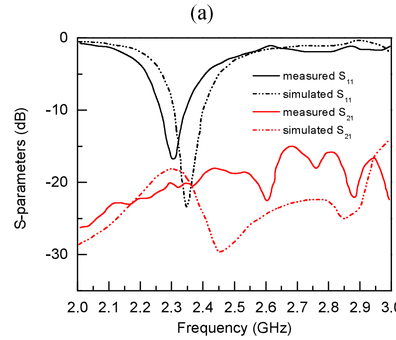


Fig. 26. Schematic of a 6-bit chipless RFID using spiral DGS integrated with circular disc monopole [31].



(a)



(b)

Fig. 27. (a) Schematic of two closely packed PIFA with defected ground plane, (b) Simulated and measured S-parameters of the PIFA [27].

E. DGS for Miniaturization of Patch Antennas

The use of DGS was explored earlier to miniaturize printed circuits, and this concept has recently been adopted to the problem of antenna designs [77]. A nonstandard DGS shape has been used below a square patch and a size-reduction of 68% has been achieved. Such DGS loads the antenna capacitively and shifts the resonant frequency from 3.63 GHz to 2.05 GHz. Yet another investigation has reported 80% reduction in size by employing slit and T-shaped DGS for a square microstrip radiator [78].

F. DGS for PIFA and Mobile Handset

Following the use of the suppression of mutual coupling [17], [63], it was also applied to PIFA [27], which is commonly used in mobile handsets. Their aim was to increase the packing density of PIFA elements sharing the same substrate. A schematic diagram along with its S-parameters is shown in Fig. 27. A subsequent work [28] claimed an $S_{21} \approx$ -40 dB for a

PIFA array using a dumbbell-type defect. DGS has also been explored to reduce the size of the ground plane of a mobile handset [79], and various shapes and sizes of DGS have been successfully explored.

VI. Conclusion

There appears to be an increasing trend in terms of research publications and patents granted during last few years in this relatively new area of DGS-based antenna design. Some major research laboratories have already adopted the DGS technique to realize advanced arrays for airborne radars, as a typical example. The topic of designing DGS-integrated antennas still remains an open book for both researchers and application engineers. There are several unresolved issues which need to be addressed in the future for further advancements in this area. These include the minimization of unwanted leakage or backward radiation through the DGS by reshaping or reconfiguring its geometry, possibly via the use of DGS in a multi-layered configuration; optimization of DGS dimension to avoid conflicts with the radiating mode; wider use to dielectric resonator antennas, to name a few.

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